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Procedia CIRP 15 (2014) 437 – 442

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21st CIRP Conference on Life Cycle Engineering

Derivation of measures for energy efficient machine design by evaluating energy consumption data

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Abstract

During a machine's design phase a lack of reliable specification data resulting from the use phase specific application leads to energy losses in various discrete manufacturing processes. The reason for instance could be inefficient design of drive components or insufficient machine control. In order to support machine designers with reliable input data to e.g. dimension drive components in energy efficient way, this contribution presents an approach how to measure and interprete energy consumption data of machines during its use phase. This can be applied to derive energy efficiency measures on components level. The identified measures then are implemented during the design phase of the next machine generation or realized during the machines use phase by energy efficient machine upgrading.

Keywords: Energy efficient design; Energy performance indicators; Sustainable use of existing machinery; Energy efficient machine upgrading; Energy efficiency in discrete manufacturing

1. Introduction

1.1. Energy efficiency of manufacturing equipment

Due to rising energy costs, one of the major challenges for machine operating companies is to increase the energy efficiency of their existing machinery in manufacturing [1, 2, 3]. Hence machine developing companies in their role as suppliers need to increase the energy efficiency of their products to create a unique selling point. At the same time considering current customer requirements and engineering standards [4, 5, 6, 7].

Especially in countries with rising energy costs for industrial consumers this leads to a reduction of energy expenses and to a reduction of manufacturing-process-related environmental impact, as well.

In this paper a new approach to increase the energy efficiency of existing machinery in discrete manufacturing is presented.

In order to explore additional energy efficiency potentials, the cooperation of machine operating companies, machine manufacturers and component manufacturers should be intensified during the design phase of machinery. Therefore a methodology to specify the requirements for the machine should be developed, which considers individual machine operating conditions. This supports engineers to design components and machines in an energy-efficient way.

doi:10.1016/j.procir.2014.06.062

1.2. Influencing energy efficiency by machine design

During the design phase, energy-relevant technical specifications of a new machine and its components are defined, which then are valid during the whole life cycle. As illustrated in figure 1 according to established engineering standards [8] those specifications influence the procurement costs (C_P) as a part of the manufacturing costs. Furthermore their efficiency influences the energy costs (C_E) as a part of the operating costs during the utilization phase. As shown in figure 1 the measurement of energy efficiency relevant data during the machine's utilization phase supports the manufacturer to develop efficiency measures during the machine design phase.

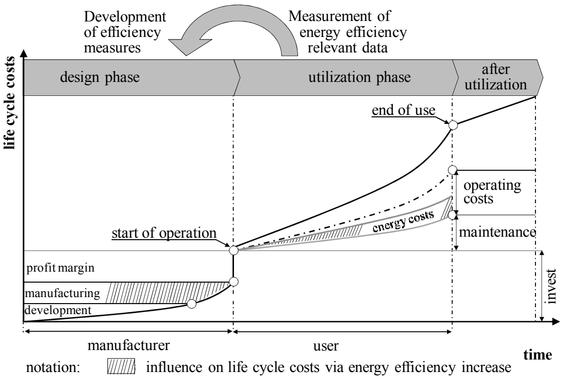

Fig. 1. Energy costs of a machine as part of life cycle costs [8].

Looking at the influence on life cycle costs using the example of designing energy efficient drives, both the procurement costs during the machine design and the energy costs during its utilization are affected. To close the information loop, the measurement of actual power consumption of a component supports the dimensioning in the right way during the design phase.

2. Derivation of measures for energy efficient machine design

In the following section Energy Performance Indicators (EnPIs) in compliance to the ISO Standard 50001 are introduced using the variable $\varkappa$. Those EnPIs are specified in order to attribute the energy efficiency measures load management, dimensioning of drive components and machine control based on the interpretation of electrical multi-channel power measurements described in [2].

2.1. Procedure to increase energy efficiency

The procedure developed by the authors [9] how to assess energy saving potentials consists of four modules. As shown in Figure 2 the first module includes the machine identification [10] and is followed by a second module for machine examination including initial power measurements. To gather the necessary input data a detailed machine examination has to be conducted using flexible measurement concepts. Those measurement concepts consider various component groups.

In order to ensure a successful application of the measurement concepts a power measurement and interpretation procedure, considering various energy-relevant operation states of machines, was developed. This provides a basis for the quantification of energy saving potentials. Subsequently the assessment of energy efficiency measures by load curve interpretation and the derivation of measures are conducted. Finally the implemented energy savings are verified by a second power measurement.

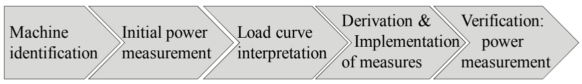

Fig. 2. Procedure to increase energy efficiency.

2.1. Assessment of load management on process level

A manufacturing system in a discrete manufacturing process consists of several machines operating at the same time. The summation of those power demands per single machine leads to a fluctuating load curve as illustrated in figure 3. Since energy providers usually charge power costs based on maximum work during a 15-minute time period, the resulting load curve should be leveled as far as possible.

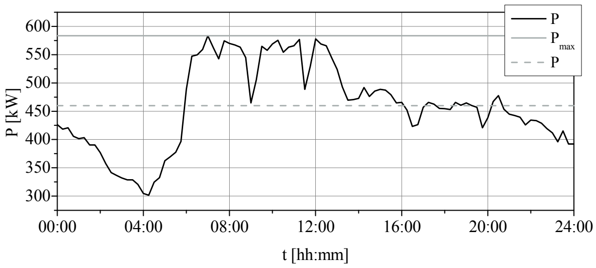

Fig. 3. Load curve interpretation to assess peak loads.

To assess the impact of a peak load P_{max} in relation to the average power $\bar{P}$ the indicator $\varkappa_{Peak\ Load}$ is defined as follows:

$$\varkappa_{Peak\ Load} = \frac{\bar{P}}{P_{max}} \tag{1}$$

2.2. Assessment of dimensioning of drive components

A main aspect of this measure is the dimensioning of the electric drives because those are the major consumers of electrical power in industry. In the use phase of production machinery specifically the electric drives are often oversized. As a consequence their degree of efficiency is not close to the possible optimum of the drive. The dimensioning of an electrical drive is usually defined during the development phase of the machine. Often there is no information about the real performance requirement available. Due to this P_{max} of electric drives is dimensioned based on expert knowledge and assumptions including a high power reserve ΔP_{nom} [11].

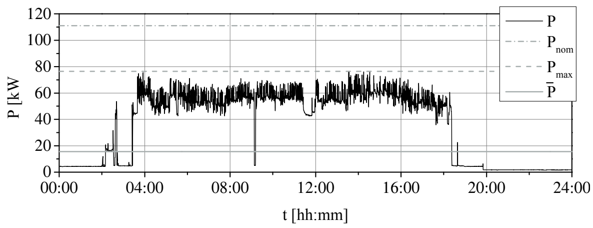

Fig. 4. Load curve interpretation to assess dimensioning of drive components.

To assess the energy efficiency of an electric drive the indicator $\varkappa_{Dimension}$ is important. Considering the variables shown in figure 4, it is defined as the ratio of maximum power P_{max} and the nominal power P_{nom} as follows:

$$\varkappa_{Dimension} = \frac{P_{max}}{P_{nom}} \tag{2}$$

2.3. Assessment of operating state specific machine control

The machine control ensures the operating state of each component according to the needed function programmed by the machine manufacturer. Considering the engineering standard ISO 14955 the main focus during the construction of a machine is to increase the productivity in the operation state of machining. Thus auxiliary components are often running continuously in order to ensure high machine availability. This is a disadvantage considering the energy efficiency of the machine. As a consequence unnecessary energy is consumed during standby. This phenomenon often can be seen on machines manufactured before 2012.

In order to reduce the energy consumption during standby (shown in figure 5) on the one hand a power reduction and on the other hand a time reduction can be applied [12, 13].

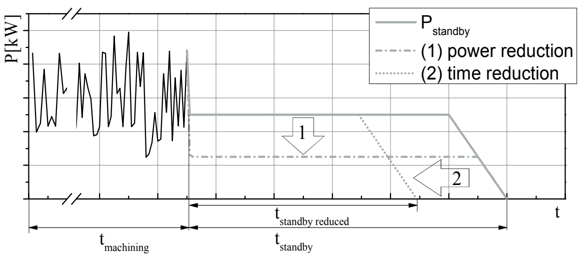

Fig. 5. Reduction of energy consumption by efficient machine control.

Evaluating the standby energy consumption of a machine during its runtime it is necessary to differentiate between the time of machining $t_{machining}$ and the time of standby $t_{standby}$.
For the assessment of the standby energy consumption there are two values needed for the calculation. By analyzing the load curve $\bar{P}_{machining}$ and $\bar{P}_{standby}$, the mean power consumption in those operation states can be identified.

To describe the ratio of the average energy consumption of the non value adding operation state standby $\bar{P}_{standby}$ in relation to the average power consumption during machining operations $\bar{P}_{machining}$ the following formula can be used:

$$\varkappa_{Standby} = \frac{\bar{P}_{standby}}{\bar{P}_{machining}} \tag{3}$$

2.4. Cost effects of energy efficiency measures during the machine's use phase

To derive measures for energy saving based on the measurement results, the three categories of measures, shown in table 1, are suited to reduce both initial procurement and installation costs as well as ongoing energy and load costs.

Table 1. Attribution of costs per category of measure.

Measure	Initial costs	Ongoing costs	Attribution of costs (phase)
Dimensioning	C_P	C_E	C_P : Design; C_E : Use
Reengineering of machine control	C_P, C_I	C_L	Use
Load management	C_P, C_I	C_L	Use
	Notation:		C_I: Installation costs, C_P: Purchasing costs, C_E: Energy costs, C_L: Load costs

3. Selected use case results

In the following section results of industrial use cases are discussed. By applying the determined energy performance indicators $\varkappa$ as dimensionless coefficients the energy efficiency of machines will be assessed. This includes a comparison between the situation before and after the implementation of efficiency measures. Thereby the procedure to derive energy efficiency measures concerning component dimensioning, reengineering of a machine control and load management is applied.

3.1. Dimensioning of electric drives

In this use case, the electric drives of a large scale plant consisting of several machines were analyzed concerning their electric power consumption during a measurement period of 90 hours. In this period a production portfolio of all relevant product variants was manufactured, including the most energy intense product.. For the main drive of this plant, a direct current motor including a gearbox with a nominal power P_{nom} of 260 kW was installed.

The interpretation of the measurement data shown in figure 6, leads to the result that a maximum power P_{max} of 179 kW was required. Hence the indicator $\varkappa_{Dimension}$ of 0.69 is valid in the current state. Considering the oversizing of this drive and its efficiency of initially 80 percent, a re-dimensioning of this drive should be applied in order to increase energy efficiency.

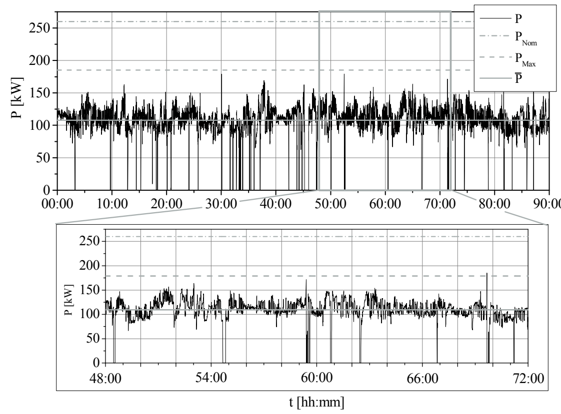

Fig. 6. Assessment of dimensioning of an electrical drive.

To reduce the identified oversizing a substitution of the main drive and the gearbox by two direct driven torque motors with a nominal power of 100 kW was identified as an efficiency measure. As summerized in table 2, this drive solution in the future state offered a better efficiency η of 91 percent. Thereby the yearly energy costs were reduced by 12 percent. This represented ongoing cost savings over the whole utilization phase of 25 years in average.

Additionally the purchasing costs C_P during the manufacturing were reduced by 30 percent, since smaller main drives were installed and the custom made gearbox was substituted by direct drive technology. As a result of these measures the Indicator $\varkappa_{Dimension}$ was improved from the value 0.69 in current state to 0.90 in the future state.

Table 2. Assessment of the measure drive dimensioning.

Variable	Initial state	Future state	Saving
Nominal power P_{nom} [kW]	260	2 x 100	-
Efficiency η	0,80	0,91	-
Purchasing costs C_P [€]	43.750	30.400	30%
Energy costs C_E [€/a]	114,682	100,819	12%
Indicator $\varkappa_{Dimension}$	0.69	0.90	-

3.2. Reengineering of machine control

Initially the electric power demand of machine tools during the different operation states machining and standby was analyzed. Looking at the standby consumptions in the initial situation, the machine required 12 A which is an equivalent of 8 kW average power $\overline{P}$. The analyzed machine spent 1,400 h/a in machining and 4,700 h/a in standby mode.

To reduce the energy consumption during longer lasting standby periods without losing flexibility due to longer warm up times a second standby mode called "standby 2" was defined and implemented. In this case the axis drives, the hydraulic pump and the cooling aggregate were turned off by the updated machine control after 30 minutes. This led to a reduced current consumption of 6 A which corresponds with a reduced average power $\overline{P}$ of 4 kW.

Figure 7 illustrates the results showing a reduction of 50 percents compared to the initial situation.

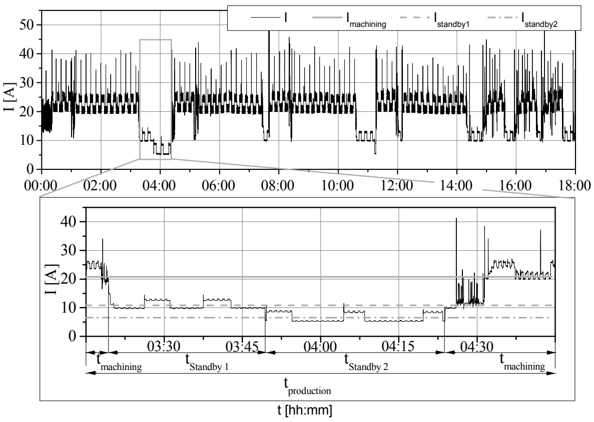

Fig 7. Assessment of standby power consumption of a machine tool.

The evaluation of the energy saving potential of this reengineering measure lead to the effects indicated in table 3.

Table 3. Assessment of the measure peak load management.

Variable (operating state: runtime per year)	Initial state	Future state
Ave. power $\overline{P}$ [kW] (manufacturing:1,400 h/a)	14	14
Average power $\overline{P}$ [kW] (standby: 4,700h/a)	8	-
Average power $\overline{P}$ [kW] (standby 1:1,000h/a)	-	8
Average power $\overline{P}$ [kW] (standby 2: 3,700h/a)	-	4
Indicator $\varkappa_{Standby}$	0.58	0.35
Resulting energy costs C_E [€/a]	8,463	6,264

As a result of this measure energy costs savings ΔC_E of 2,199 Euros per year were realized (26 percent). Looking at the defined indicator $\varkappa_{Standby}$ a reduction of 39 percent was achieved. This measure was implemented on several similar machines at the same company which multiplied the effect several times.

3.3. Load management

Using a methodology described in [10], five identical machines were indentified to be investigated in detail. Looking at the measurement results which were gathered by electrical power measurements during a period of one month, a fluctuating power demand was revealed. For each machining cycle nearly triangular shaped characteristic load curves were identified. This shape repeated depending on the applied cycle times per workpiece between 6 and 17 minutes. Figure 8 shows the electric power demand of the day with the highest resulting peaks that occurred during the measurement period. The demand of electric power of each machine was measured with a resolution of 1000 samples per second and then recorded as average values within a period of five seconds.

Summing up the power consumptions of all five machines a maximum power demand P_{max} of 979 kW in total was revealed. The calculation of P_{max} as the maximum power demand within a period of 15 minutes P_{max} leads to a maximum of 486 kW. This value is relevant for the billing of electricity costs by the energy provider.

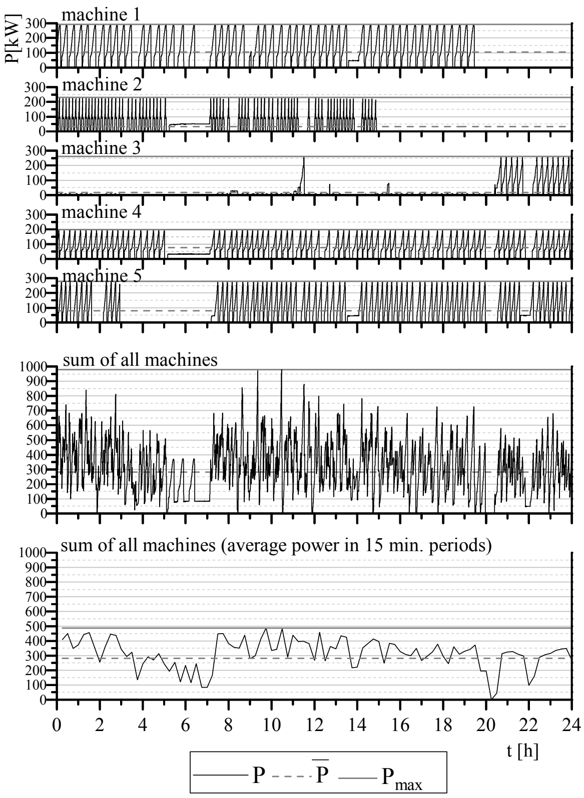

Fig. 8. Load curve of 5 machines - initial state.

In German industry the specific power costs of 50 € per year and kW are widely spread. In order to reduce the annual power costs C_P of initially 24,300 € a solution for peak load management by leveling the maximum power demand P_{max} was developed. To accelerate the computation of the input data the characteristic shape of the load curves was substituted by triangles. Figure 9 shows the principle of this substitution. After this simplification, all permutations of possible load curve combinations were assessed concerning the height of the resulting P_{max}.

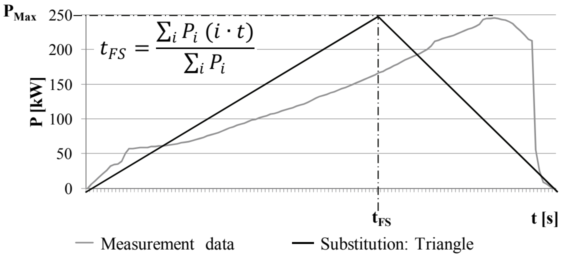

Fig. 9. Substitution of load curves by triangles.

For the combination with minimum P_{max} the resubstitution of the triangle shapes by the real measurement data was conducted. As a result the future state load curves of 5 analyzed machines shown in figure 10 were calculated.

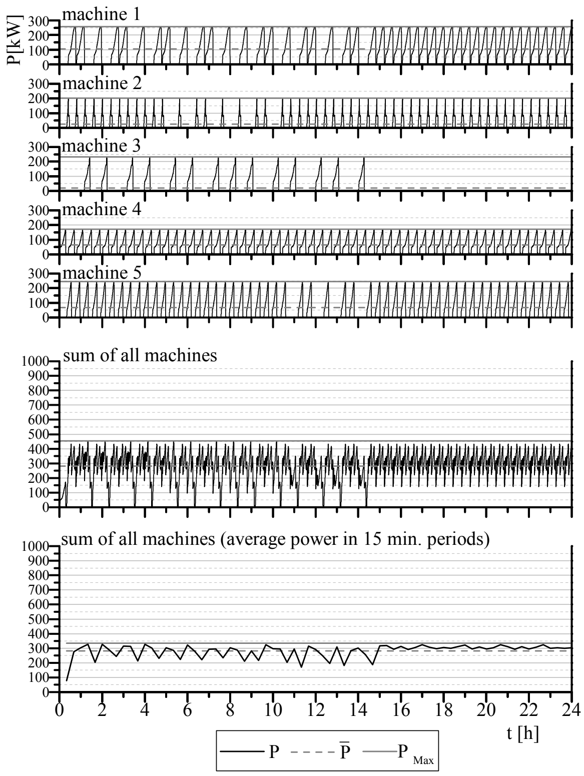

Fig. 10. Load curve of 5 machines - future state.

The implementation of the developed approach for load management leads to power cost savings of 31 percent. Table 4 gives an overview of the maximum power consumptions during initial and future state. This approach is suited to be applied on other machines running at the same time. As a precondition, an overcapacity of machines is needed to implement the leveling of resulting load peaks. Hence flexibility is a critical success factor to realize the energy costs savings, which have to fit in common targets in manufacturing like short lead times.

Table 4. Assessment of the measure peak load management.

Variable	Initial state	Future state
Average power $\overline{P}$ [kW]	282	282
Maximum power P_{max} [kW]; 5 sec.	979	453
Maximum power P_{max} [kW]; 15 min.	979	453
Indicator $\varkappa_{Peak\ Load}$	0,64	0,84
Resulting power costs C_P [€/a] (extrapolated to period of one year)	24,300	16,750

5. Conclusion

The developed procedure including the EnPIs represents an approach to be integrated into product labeling and energy benchmarking of machines.

Applying the approach in several use cases, it was successfully evaluated regarding the requirements formulated at the beginning. Thereby the following benefits for the companies were obtained. Their impact was assessed as follows:

- By introducing peak load management, an energy costs saving potential of 31 percent, resulting from a reduced electrical maximum power demand was identified.
- Using the example of an electric main drive of a large scale machine, the dimensioning of components led to energy reduction of 12 percent, along with a reduction of procurement costs for relevant drive components of 30 percent.
- By the implementation of an operating state-specific machine control at several machine tools, the energy consumption of the machinery in standby mode has been cut by half. This led to energy savings of 26 percent.

Looking at the results realized during the industrial case studies, the consistent application of the developed procedure provides a significant contribution regarding energy efficiency in discrete manufacturing.

6. Outlook

To further reduce energy costs as well as manufacturing-process-related environmental impacts, the following topics should be considered as future research activities: In addition to the indicated technical measures to increase energy efficiency, it is necessary to develop human-oriented measures in order to increase energy efficiency. Hence the application of information technologies in order to visualize the current energy consumption, which can be influenced by machine operators, would cause transparency in an activity-oriented way. This would offer support in deciding how to operate machines in an energy efficient way. Furthermore possible approaches to integrate energy efficiency optimization of existing machinery in maintenance processes have to be investigated. During the use phase of machinery, this offers recurring cases to implement reengineering measures at manufacturing machinery.

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